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MULTIDISCIPLINARY DESIGN PRACTICES FROM THE F-16 AGILE FALCON*

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ABSTRACT

An advanced version of the F-16 called the Agile Falcon was studied and a preliminary design was developed in the late 1980's. Multidisciplinary design issues were addressed through trade-offs at the conceptual and preliminary design levels. Trade studies and associated approaches from a perspective of how they effected the course of the design process are discusssed. The interest of the Agile Falcon was directed at a balance of multirole capability. The results of the studies focused the airframe toward an F-16 type trapezoidal wing. Ensuing studies involved optimization of the wing to maximize the multirole capacity while constraining/minimizing impact to existing hardware. The redesign of the wing touched all aspects of the airframe and subsystems.

INTRODUCTION

In the early 1980's General Dynamics Fort Worth Division (now Lockheed Martin Tactical Aircraft Systems) conducted studies to investigate the incorporation of advanced technologies into an F-16 with a larger wing. The interest was directed at maintaining a balance of multirole capability. The results of the studies focused the F-16 variant, called Agile Falcon, toward an F-16 type trapezoidal wing. Ensuing studies involved optimization of the wing to maximize the airplanes multirole capacity while constraining/minimizing impact to the fuselage and empennage. The redesign of the wing however touched all aspects of the airframe and subsystems.

Multidisciplinary, multi-objective design issues drive aircraft design. For example, the Agile Falcon program was focused to enhance the F-16's current state of agility. The agility measure includes multi-objectives of maneuverability and controllability. Difficulties in design decisions arise from the uncertainties of what one might categorize as the weighting factors of a system-level, multi-objective function. In other words, priorities of the multiple objectives in a system design are usually not clear. The Agile Falcon program[1] attempted to address these issues in a systematic approach in the predevelopment stage prior to full scale development. Figure 1 depicts the Agile Falcon at the end of its predevelopment phase in 1989.

Figure 1 Agile Falcon At Completion of Predevelopment Program

Methods used in the data development to support the Agile program have since evolved. For example, a combination of computational fluid dynamics analyses (CFD) and wind tunnel testing would be used in lieu of extensive wind tunnel testing for performance and stability and control data acquisition. In this paper, methods and processes used in the Agile program are examined and compared to those that might be used if the Agile Falcon were being developed today.

Agile Falcon Objective

The F-16 was born in the 1970's from the light weight fighter program. Over the last 20 years it has provided the Air Force both air-to-air and

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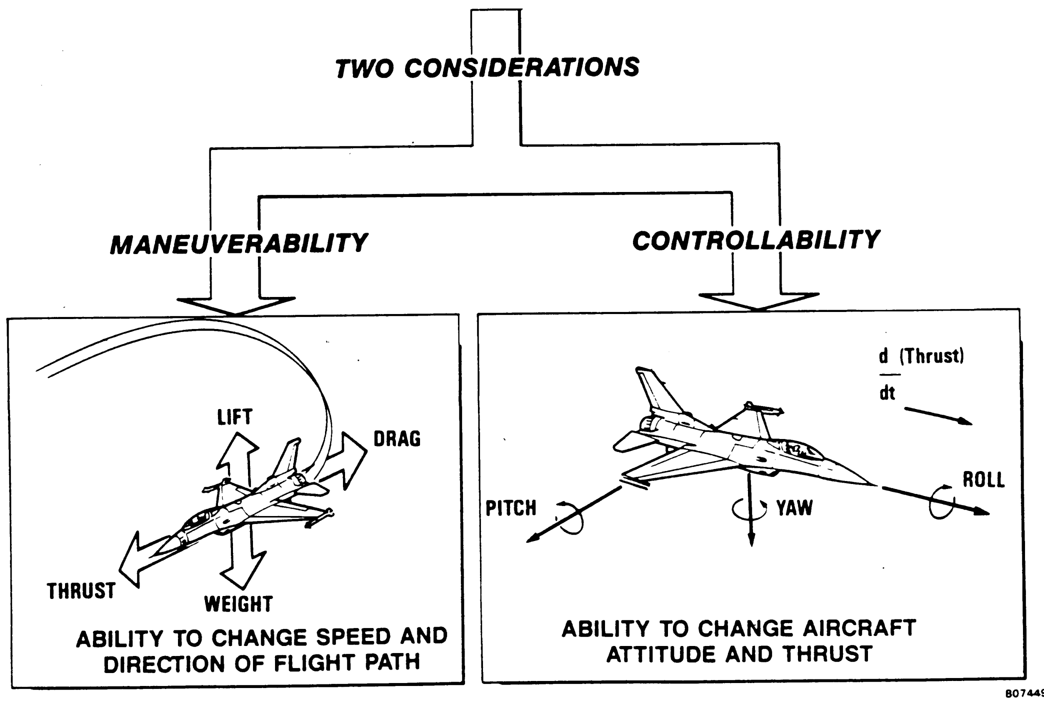

Figure 2 Characteristics of Agility

air-to-ground combat capability. Its light weight and efficient aerodynamic design have provided outstanding agility characteristics. Advanced versions of the F-16, however, are less agile than its earlier versions. Increased capabilities in areas such as pilot awareness have led to increased vehicle weight. Studies were initiated in the 1980's to regain F-16A agility.

Many papers in the 1980's discussed the topic of agility[2,3] In reference 1, agility in a fighter aircraft sense was defined as "performance needed to win and survive close-in combat." Furthermore, maneuverability and controllability as they are related to agility are discussed as shown in Figure 2. "Maneuverability is the quality that changes the flight path vector of an aircraft. It results from the sum of forces (lift, weight, thrust, and drag) that cause a change in the speed and direction of the flight path. Controllability is the ability to guide flight path changes." Maneuverability leads to such measures as turn rate, acceleration and deceleration. Controllability leads to such measures as rates and accelerations of aircraft states.

Together, controllability and maneuverability in a fighter aircraft allow its pilot to win "dog fight" encounters with opposing aircraft. A pilot will call on the aircraft, for example, to turn, accelerate, turn again, decelerate, fire a missile, and accelerate suddenly to gain the advantage on another aircraft and win a "multi-bogey" engagement.

In order to address maneuverability and controllability, the Agile Falcon program focused on the development of an advanced wing and wing/strake/fuselage integration. Trade studies were performed to develop information measuring agility as defined through controllability and maneuverability metrics as related to geometric variations of the wing and wing/strake/fuselage integration.

DEVELOPMENT APPROACH

A predevelopment program was executed to improve turning performance, increase the AOA capability, maintain adequate controllability in the roll axis throughout the AOA envelope, and minimize impact to existing systems on the F-16. The turning performance and AOA capability are consistent ingredients to maneuverability. Controllability in the roll axis was emphasized at high AOA to allow sudden changes in flight paths while allowing maximum maneuverability. All existing systems on the F-16 were evaluated to constrain/minimize cost impact from wing/strake/fuselage modification.

Two of the airframe studies will be used to illustrate how agility was addressed during the Agile predevelopment phase. One study involves the overall synthesis of a baseline wing/strake/fuselage configuration; the second illustration encompasses development of the wing design within the context of the baseline configuration.

Baseline Wing/Strake/Fuselage Configuration

Prior to the predevelopment program, concept sizing studies were performed to define a neighborhood for potential Agile Falcon solutions. These studies included traditional parametric databases for weight, costs, and aerodynamics. These databases were founded on the F-16 and provided stable measure for sensitivity studies. The study-results led to selection of a matrix of wings and strakes to build a more accurate parametric space and provide refinement to a baseline wing/strake/fuselage configuration. The selected configurations are depicted in Table 1 and Figure 3.

This matrix of configurations included 3 strakes in combination with 7 wings. The Baseline wing was derived during the aforementioned synthesis study. Data was developed for these configurations with regard to agility characteristics and structural integration.

The agility characteristics were studied through the combination of wind tunnel tests followed by analyses. The structural integration studies included airframe layout studies combined with preliminary level aeroelastic synthesis evaluation. The data developed in these studies was combined in a qualitative evaluation.

Table 1 - Candidate Wing Configurations

Config.	Span (ft)	Area (sq ft)	Sweep
# 1	37.50	375	40.0°
# 2	35.07	375	37.5°
# 3	35.07	410	37.5°
# 4	35.07	328	37.5°
# 5	33.54	375	37.5°
# 6	37.50	375	37.5°
Baseline	37.50	375	34.3°

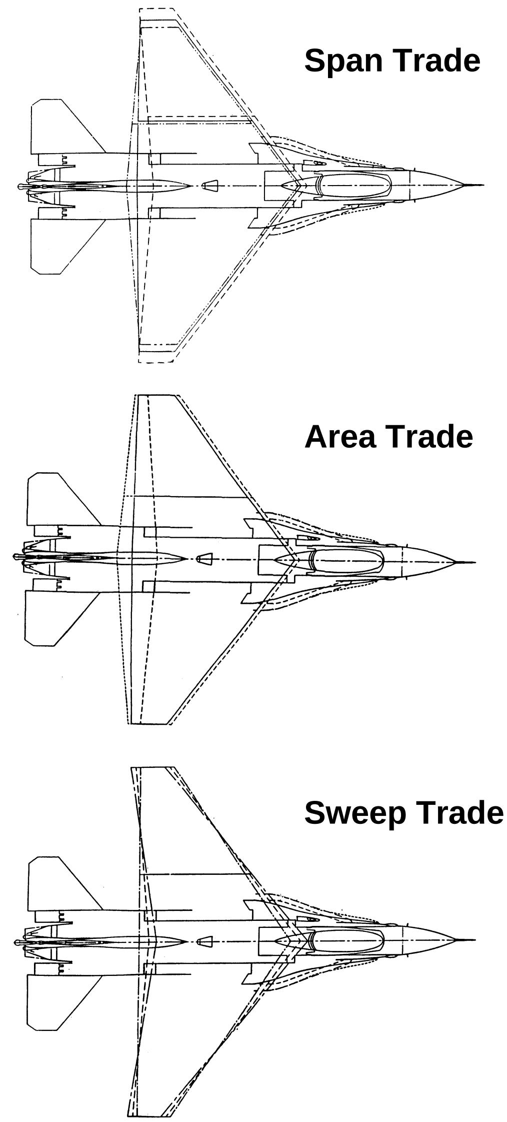

Figure 3 Three Planform Trades

Agility Characteristics

Figure 4 presents the flow of wind tunnel tests and analyses performed in the matrix study. Two series of tests were performed to provide a screening process for the later more expensive transonic tests. The configurations tested were “full-up” F-16-like models (1/9th scale). As seen in the figure, the first set of tests concentrated on an understanding of characteristics in extended regions of AOA where basic lateral directional stability and

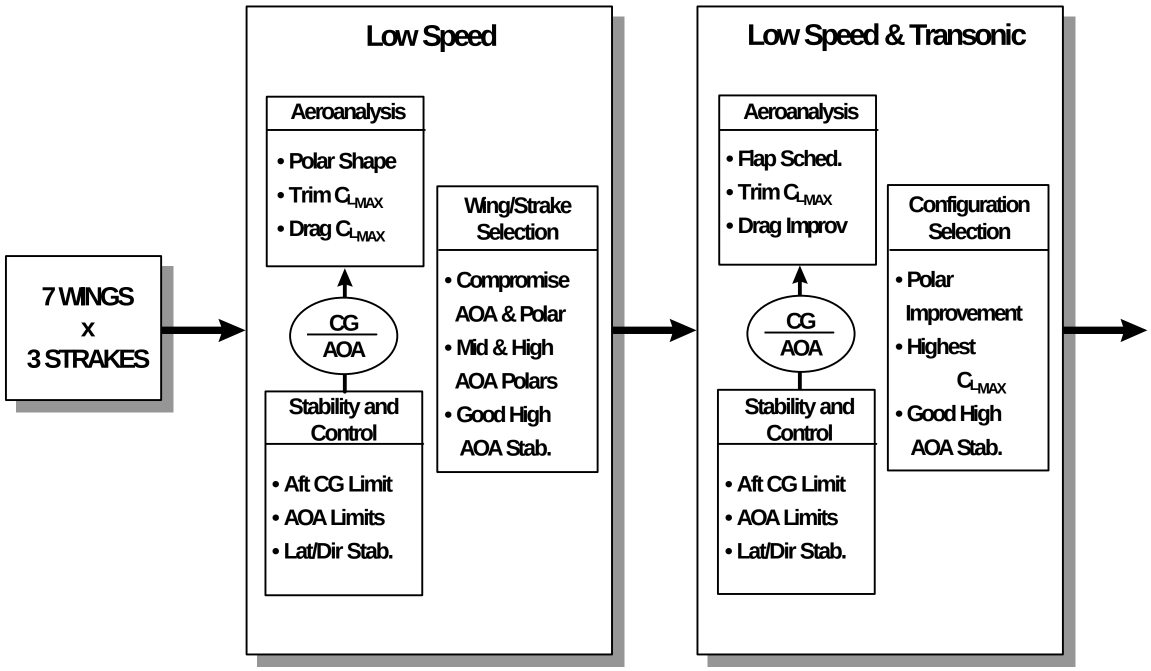

Figure 4 Aerodynamic and Stability & Control Screening Process

C_{LMAX} could be evaluated. These parameters are key in the maneuverability and controllability area. A Taguchi experiment was performed during the wind tunnel testing to reduce follow-on low speed and transonic testing. From the results of the first tests, a down-select to one strake/4 wings was made for the follow-on combined low speed and transonic testing.

In the testing, no one configuration provided superior performance in combined C_{LMAX} and stability in extended AOA. However a cluster of 3 configurations seemed to be the best performers: 2, 3, and 6. General conclusions from a stability and control viewpoint included (1) minimizing span and (2) moving the wing aft for balance. Conclusions from an aero/performance viewpoint included increasing L/D with span and increasing C_{LMAX} with area. Both disciplines also recommended continued tailoring of the wing/strake area as key.

Structural Integration

Structural evaluation of this matrix involved quantitative and qualitative studies. Structural sizing issues needed to be evaluated as well as system integration issues. Benefits from any aerodynamic configuration selected should not be impeded by structural weight increases, wing deformation characteristics, or system changes.

The Wing Aeroelastic Synthesis Procedure, TSO, was used to evaluate structural sizing issues[4,5]. All of the parametric variations in wing span, wing area. and wing sweep were studied. Design optimization was performed in each case for a variety of objective and constraint functions. In addition to the planform variations, a study of wing t/c and material properties was included.

Typical optimization results for varying concepts of aeroelastic tailoring are shown in Figure 5. The wing box skins were designed in each configuration for three different design goals/concepts. A minimum weight "Strength Sized" design was achieved with three aircraft simulated maneuvers (two symmetrical pull-ups and one asymmetric rolling pullout). In the second concept, a flutter requirement and an aileron roll control effectiveness requirement were added to the strength requirements ("Aeroelastic Sized"). The third concept added an aeroelastic twist requirement to the strength and aeroelastic requirements. The aeroelastic twist provides lift-to-drag efficiency at the simulated turn maneuver point.

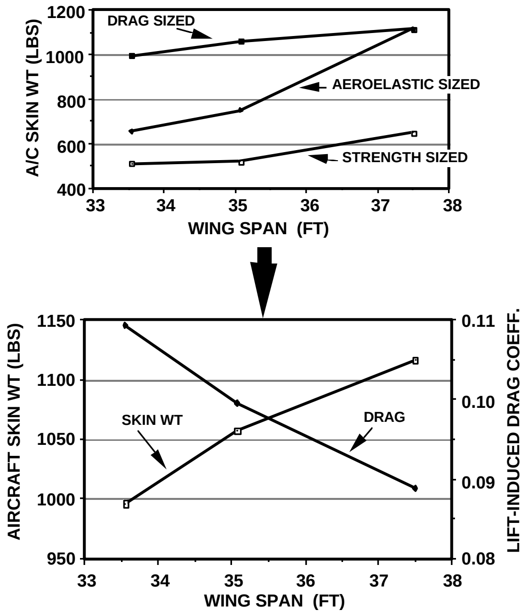

Figure 5 Optimization Study Examined Weight, Design Concepts, and Performance

The top part of Figure 5 displays the sensitivity of the wing box skin weight with respect to the concepts and span. The span study (shown above) provided the greatest sensitivity while the sweep (not shown) provided the least. The bottom part of Figure 5 provides the sensitivity of the aeroelastic drag to the wing skin weight for the "Drag Sized" concept. Interestingly, the area study (not shown) indicated that as area increased, the weight decreased to a point before beginning to increase. This observation was rationalized by the increase of wing depth for a fixed t/c allowing for gains in structural efficiency up to a point. Therefore, Configurations 2 and 3 provided interest for further study.

Airframe layout studies were performed to examine system interface issues. Considered in these studies were landing gear placement, engine and engine accessories placement, interface of fuselage-based wing control surface actuation subsystems, interface of wing/fuselage fuel systems, and wing/fuselage interface loads. Structural arrangements studies involved placement of wing spars and ribs as well as fuselage carry-thru bulkheads. Qualitative assessments were made with regard to ease of integration. Configurations 2 and 3 were the highest ranked.

Quantitative assessments were made in terms of mass properties estimation for each configuration. Although these estimations were parametrically based, the aforementioned TSO studies (a subset of the estimates) substantiated the findings. The results were provided to various analysis groups to evaluate performance and stability.

<u>Selection of New Baseline Configuration</u>
Derivation of a new baseline from this information was performed through a qualitative analysis. Stability and Control considerations led to the conclusion that the baseline span of 37.5 feet needed to be reduced. Aerodynamic performance considerations lead to the conclusion that although increased span over the F-16 provides substantial improvements in L/D, increased span with increased area might provide enhanced stability with no degradation in L/D. Figure 6 illustrates this in showing the sensitivity of $C_{L_{MAX}}$ and C_D at $C_{L_{MAX}}$. The increased area provides for the aft shift of aerodynamic center for stability considerations while allowing the increase span for L/D

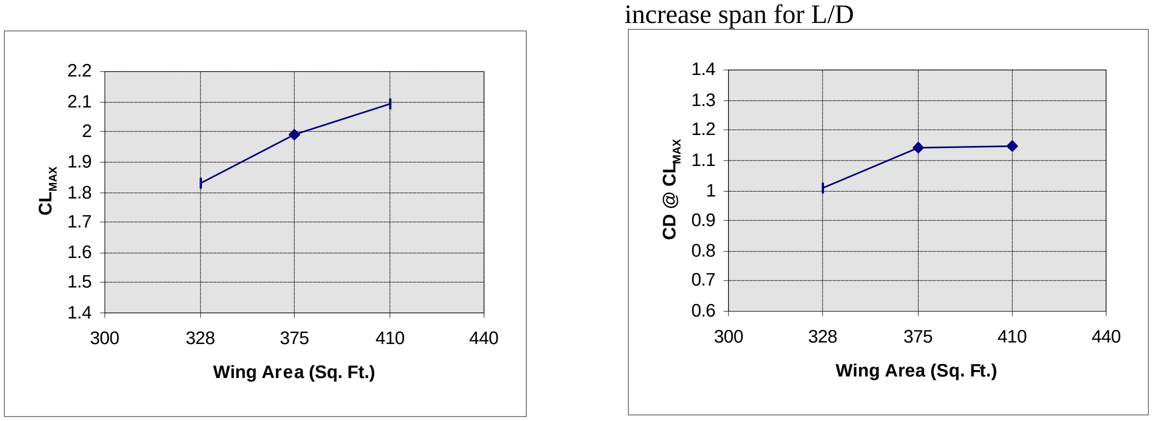

Figure 6 Sensitivity of L/D @ CL_{MAX} With Wing Area

performance. Figure 7 shows data from the TSO study indicating that an increase in area with fixed t/c could offset an increase in span in terms of structural weight.

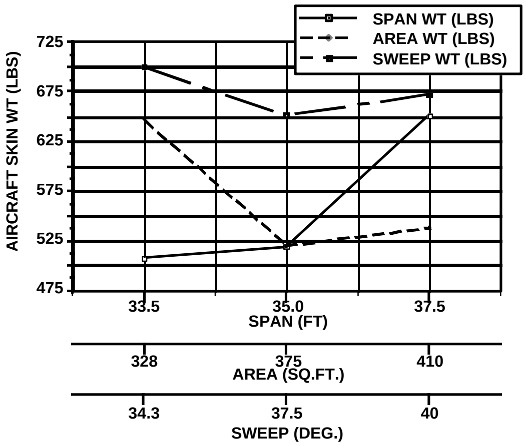

Figure 7 Weight for Area Increase at Fixed Span Offsets Weight for Span at Fixed Area Increase

These pieces of information coupled with the system interface studies led to a new configuration baseline. The process for determining a new configuration involved an integrated product team approach considering the positives, negatives and sensitivities of the aforementioned studies. While the system integration studies are not shown, they provided indications to ease of design and manufacturing assembly, as well as costs of the Agile Falcon. The new configuration was determined through a combined selection of wing-span, wing-area, wing-sweep, strake, and wing-placement with respect to the fuselage.

Impact of Design Technologies On Approach

While the study to establish a refined baseline involved development of multidisciplinary sensitivities, the number of data points established was few; and the ability to establish an accurate parametric connection of the data to agility was not there. For example, each of the wings studied in the matrix allowed for integrated computation of turn rate performance, which involves L/D, $C_{L_{MAX}}$, and airframe weight. There was not enough time or information, however, to integrate controllability measures. Time history maneuvers would have allowed characterization of the vehicle's full agility. Finally, three points in sweep, three in span, and three in area as considered in the wing matrix study, allowed characterization of a second order curve of information. However, there was always question on information distant from any of these points.

With the current capability of computational fluid dynamics, enough wing/strake/fuselage combinations could be evaluated and transformed into response surfaces to allow consideration of a design space, rather than a sampling of the space. Similarly, the ability to develop structural finite element models and perform ASTROS-like design optimization studies[6,7] would allow structural evaluation on a finer level. Response surface techniques lend to design of experiment approaches[8]. Given such methods, syntheses can be performed that allow examination of many configurations approximated through the response surface. Agility metrics involving controllability and maneuverability could be evaluated and factored into battle scenarios.

Parametric modeling of aerodynamics and structural configurations is imminent. Design of experiment approaches may occur in an automated fashion in the future. A missing link is the development of techniques for control law modeling to allow parametric time history evaluations in rapid fashion.

In the case of an active aeroelastic wing, redundant controllers can be used with augmented control objectives where force imbalance constraints are combined with maneuver load control metrics to achieve control surface gearing per maneuver[9]. A generic control approach[10] may also provide initial through-put for DOE in the design of airframe. The issue lies in the overall vehicle synthesis, its mission scenarios and overall vehicle class (e.g. subsonic attack vs. supersonic air superiority). Often the metric for design is not clear. The question to be answered is how a vehicle will be used and how it will respond in a combat environment. To perform such simulation, integrated measures of agility are required. Response surfaces can allow rapid evaluations of inputs to the agility measures such as turn rate over a wide range of geometric variables.

Much of the data developed with regard to system integration was qualitative, requiring "man in the loop" to evaluate the many possibilities. Genetic algorithms combined with object oriented modeling languages may serve to automate systems integration. Object oriented approaches to conceptual design are being explored[11,12].

Not presented here is any approach to bring affordability into the decision process. This metric is a function of many discrete decisions that are linked to materials and manufacturing processes. Historically, we have relied on weight-based cost. It is conceivable that object oriented approaches may enable rapid evaluation of activity based costs as functions of geometric parameters and inclusion of such data as an independent variable.

Wing Design

The wing design integrated three studies toward enhanced agility for the Agile Falcon. An aerodynamic performance study focused on the development of the wing twist and camber distribution for maximum maneuverability. The objective of the study centered on a balance in high-g turn objectives and 1g acceleration objectives. Controllability studies focused on definition of the control suite of the wing to satisfy low speed (high AOA) and high speed (structural flexibility) handling qualities. An outboard aileron was considered in addition to the F-16 baseline flaperon (inboard trailing edge surface). The structural studies included an assessment of aeroelastic tailoring strategies that would best complement the maneuverability and controllability initiatives. The evaluation criteria for the three studies consisted of measurement in (1) turn rate, (2) roll performance, (3) structural weight (wing and fuselage), (4) impact to fuselage structure and fuselage based systems, and (5) airframe producibility. The present discussion of the wing design is presented from the bias of the structural studies and where they interfaced with the aero/performance and stability and control studies.

Focus on Structural Studies

The baseline material for the Agile Falcon wing skin was advanced graphite composites. Extensive material trades were performed. Within these trades was a study of aeroelastic tailoring. Three concepts were derived: (1) Washout - minimum weight including a constitutive tendency of the wing to twist negatively with positive bending; (2) Washin - minimum weight including a constitutive tendency of the wing to twist positively with positive bending; (3) Strength - minimum weight with the requirement that the wing only meet general strength integrity. The objective of the study was to find the aeroelastic tailoring concept most suited to benefit the aero/performance and controllability studies. Included in the sizing were detailed requirements such as buckling, bolted joints, fuel pressure, and wing skin producibility.

The process of sizing and evaluation is shown in Figure 8. The TSO program[13] had been used in the context of internal loads development for over ten years at the point of this application. Interface tools were developed to allow the mapping of TSO results to a finite element model. The MODGEN program was tailored to the quick development of wing finite element models. The process of a TSO skin development study and a wing finite element model at this time was approximately an eighty hour task. The wing model was attached to a stick fuselage representation allowing fast evaluation of flexible aerodynamics in the FLEXLODS code[14]. A critical loads study was performed for some time on the Agile program, so therefore, identification and mapping of a critical loads case simply involved derivation of the aeroelastic tailoring concept and associated aeroelastic increments to the model. Each concept was then uniquely sized with an in-house tool known the Composite Panel Analysis Package (CPAP). A new set of aeroelastic analyses were conducted for the resized concepts. Aeroelastic deformation data was provided to the aero/performance group allowing integration of aeroelastic increments to the drag polars developed for candidate rigid wing distribution shapes (rigid camber and twist). Flexible-to-Rigid ratios were provided to the stability and controls group and applied in a 6-DOF simulation.

The aeroelastic tailoring concepts were selected for detailed study for various reasons. The Washout concept

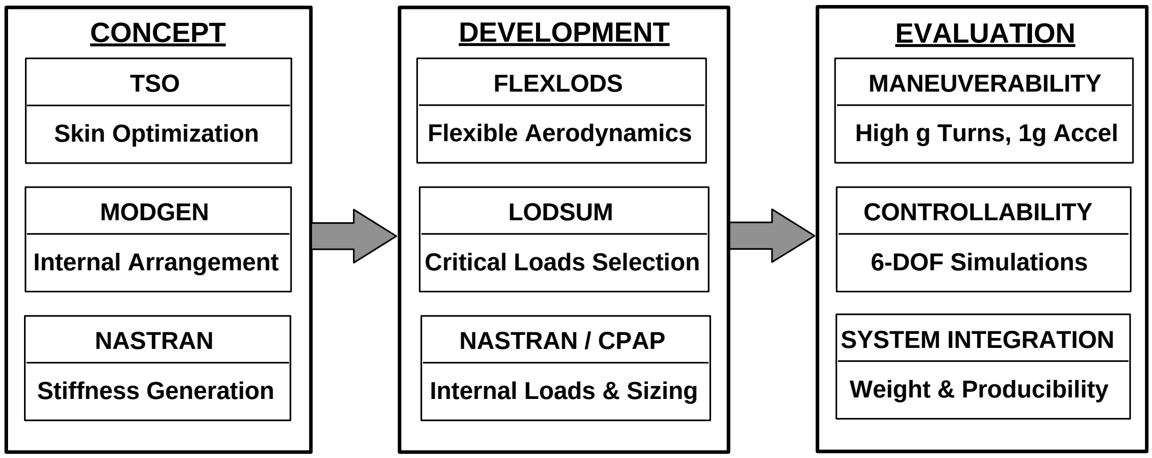

Figure 8 Aeroelastic Tailoring Concepts Were Systematically Evaluated

demonstrated, in the Validation of Aeroelastic Tailoring program through wind tunnel tests, a 23% reduction in lift-induced drag over rigid aerodynamics. The Washin concept is noted for its propensity to maximize lift and control surface effectiveness. The Strength concept allows for minimum weight and presumes that enough control effectiveness is available through redundancy. Each concept has valid benefits.

The ranking of the concept results in the study is presented in Table 2. The Washout concept provides the best overall performance to the design metrics.

Table 2 Ranking of Aeroelastic Tailoring Concept Results

Concept	Maneuver	Control	Weight	Produc-ibility
Washout	1	1	2	2
Washin	2	2	3	1
Strength	1	2	1	3

In the Maneuverability category, analyses were performed for loiter, maneuver, and acceleration. Wing deformation information was provided in a semi-empirical, linear superposition code that was tuned to rigid wind-tunnel data. Therefore, analysis credit was acquired for aeroelastic increments. The distinguishing characteristics involved the negative bend/twist coupling of the Washout concept, allowing minimum jig-shape camber and twist. The Washout concept then excelled in sustained turn rate and acceleration.

The distinguishing feature of the Washout wing in the Controllability metric is its relief of roll damping while retaining roll control. The roll control of the Washin and Washout is comparable. The damping behavior of the Washout and Strength concepts is comparable. Figure 9 illustrates the difference in roll rates for the three concepts in 1-DOF simulation. The data are normalized to the Washout concept. The project also compared the Washout, Washin, and Strength concepts in 6-DOF simulations. Other 6-DOF simulations were performed for configurations with outboard aileron combined with the inboard flaperon. These controllability studies were performed at high speed / high dynamic pressure, and the results were considered in combination with low speed handling quality studies where wing flexibility is not the issue. At the time the Agile Falcon program was canceled, the baseline configuration consisted of a single inboard flaperon with the Washout concept.

The weight metric includes the wing weight and impact to fuselage weight. Considering wing weight alone, the Washout concept is the heaviest. However, due to the load relief and distribution of load at the wing/fuselage interface, the Washout concept surpasses the Washin concept in minimum weight. The load relief and load distribution of the Strength concept is similar to that of the Washout concept and is the lightest weight concept to begin with.

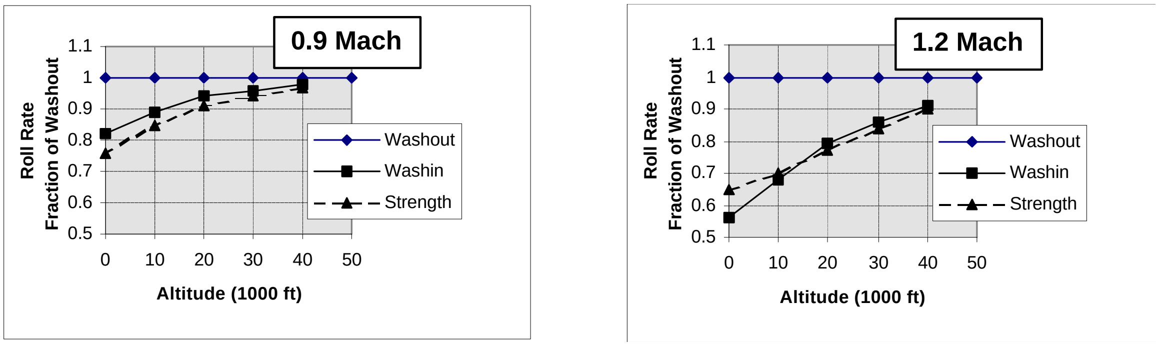

Figure 9 Roll Performance of Aeroelastic Tailoring Candidates

Producibility is measured by the gradient of thickness changes per orientation over the entire wing skin. For manufacturing, the wing skin needs to be dividable into areas or zones of constant thickness per orientation. The Strength concept was derived from the gradient-based optimization of TSO, and it was the most complicated laminate wing skin definition. While the Strength concept was developed through design optimization, a more structured approach of "pre-zoning" might be taken to improve its producibility. The same might be said for the Washin and Washout approaches. The Washin design has the fewest number of zones because its percentage of thicknesses per orientation remains approximately constant throughout the wing skin. The Washout concept could be broken into a producible number of constant percentage zones and overall thicknesses. The Strength concept, as it was derived, would require a large number of constant percentage zones.

Impact of Design Technologies On Design Approach

Like the vehicle synthesis phase of the Agile Falcon program, the approach to achieve integration would probably be the same today as in 1988-89. The differences in the overall process would be in the tool selection for developing the data and the amount of data generated to perform the needed evaluations.

Recent directions in development of ASTROS[15] and NASTRAN[16] allow that there is little need for TSO in this phase of design. Design optimization with nonlinear aerodynamics (such as CFD-based pressures) is becoming a reality. However, the aeroelastic increments would still be computed with linear aerodynamic influence coefficients. Codes such as ISMD from Boeing North American[9] even make it possible to consider the aerodynamic design of wing camber in the structural design process. The computation of accurate lift induced drag is complex, however, and the trends at best are the only thing believable. A design-of-experiments approach could be used with a modal- based design optimization[17] to arrive at optimal camber and robust structural design[18]. In addition to deriving optimal camber, ASTROS and ISMD could be used in an active aeroelastic wing approach to evaluate interaction with control laws with redundant control effectors.

In the Agile Falcon approach, only the wing structure was sized per concept. The load distribution at the wing/fuselage interface was considered qualitatively in a weight measure for the wing skin concepts. However, the true measure is in the sizing of the fuselage structure. The wing is a very small percentage of the basic design flight gross weight. Saving weight is important, but the center fuselage is densely packed with systems and loads. It is important to be able to quantify the benefits of redistributing loads across the fuselage, which aeroelastic tailoring accommodates. Today's technology allows for this.

Maneuverability evaluations could be developed today in the CFD realm with aeroelastic deformations superpositioned on the rigid geometry and the trim state provided at 6-DOF trim conditions to create a "rigid" CFD configuration for analysis. These shapes could be used for CFD-based drag computations. Of course, the test-anchored linear superposition approach could be used again. There still appears to be no tool that can adequately handle an iterative CFD-based nonlinear aeroelastic solution for a full aircraft configuration, although many are pursuing such a tool.

The process for Controllability studies would be little different today. The time to achieve this analysis would be shortened, and the number or conditions evaluated would be greater. Designs in the near future might aggressively pursue an active aeroelastic wing approach, which would necessitate a tight connection between the structural design and the control law design. In other words, the robustness of the control system would depend on the robustness of the structure[18], since an active aeroelastic wing approach consists of a “strength” concept for composite tailoring. The design of the structure is tightly coupled to the assumptions of the control laws. There is currently little feedback of requirements from the control law group until after the structure is designed. Today, conservative assumptions are made to ensure the structure covers all reasonable usage of control effectors in the development of loads. Minimizing loads and minimizing structural weight drives the control laws to a tentative state. A key area of technology development is a process and tools for performing controls/structures feedback early in the design process that allows the designer to focus on robustness issues.

Affordability is the metric of the day, and it typically factors in producibility. ASTROS and NASTRAN have design variable definition options that allow the user to maintain control of thickness gradients over the topology during design optimization. The design results would then be mapped to electronic CAD datasets for further evaluation. Tools such as PICASSO[19] were developed during the Agile Falcon era to begin to address these issues. PICASSO maps zones of constant percentages and thicknesses into composite ply tables that interface from zone to zone. This tool allows the rapid deployment of tailored laminates to producibility evaluation tools. In addition, a study today would include mapping the manufacturing data back on the internal loads model for an analysis iteration prior to sizing convergence.

As we look further to the future, parametric and associativity concepts will allow us to consider more items simultaneously in the design study. Structural arrangement versus system integration may play greatly into the structural weight computations. As was mentioned, in the Agile Falcon approach, the load distribution at the wing/fuselage interface was considered qualitatively in a weight measure for the wing skin concepts. In the future, resizing of the fuselage structure could be considered for various structural arrangements that accommodate subsystems in the overall configuration.

SUMMARY / CONCLUSIONS

The Agile Falcon program was a program focused on multidisciplinary design optimization. The objective was to maximize the agility of the F-16C while minimizing cost to do so. The objective was decomposed into developing a design focused on enhancing maneuverability and controllability while minimizing impacts on aircraft weight and subsystems.

This paper examined two central studies performed in the course of the program; (1) refinement of a wing/strake/fuselage configuration, and (2) development of the wing design including structures definition, aerodynamic jig shape, and selection of the control effector suite. These studies required coordinated efforts to bring data together at key decision points. Decisions were made in the configuration development on the basis of quantitative and qualitative assessments. No formal recomposition of the design metrics was performed to evaluate whether an optimum was achieved. However, it was determined that the product concept was improved at the completion of the predevelopment program.

If the design were being performed today, the emphasis on higher resolution would drive the number of data points considered. Computational capacity continues to grow in terms of accuracy and turn-around. Tighter integration is evident in many areas, allowing closer evaluation of multidisciplinary couplings. However, it seems that to truly use multidisciplinary design, a system level evaluation must be maintained to recompose sub-level studies into system level payoffs.

Although it is obvious, one would be remiss to not make a statement on the importance of culture. The nature of the Agile Falcon and the personalities involved allowed the program approach. Integrated design is a conscious effort of tasking processes to develop essential knowledge allowing strategic decisions that account for all design requirements. It is mission dependent. For instance, a design more prone to flutter requires more flutter analyses during the course of design. It relies on trade studies. The LMTAS integrated philosophy is to ensure that essential requirements are considered during the trade study process. The strength of LMTAS integration is derived historically from the coordination skills of our Design function[20]. New design technologies may well redefine "Design," but they will not be accepted until the culture accepts them.

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